



Recommendations for future sub component tests

EUDP: Experimental Blade Research – Phase 2 (EBR2). Milestone 6

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EUDP: Experimental Blade Research – Phase 2 (EBR2)

Milestone 6: Recommendations for future sub component tests

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1 INTRODUCTION

In the design process of wind turbine blades, tests on several scales can be performed in order to estimate the material properties and to verify the computational design models used to estimate the load bearing capacity, see Figure 1. However, currently only coupon and full-scale test are needed in order to certify wind turbine blades.

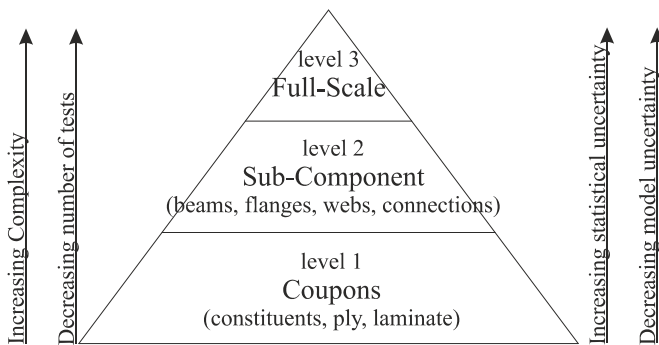


Figure 1. Illustration of type of tests which can be performed for assessment of load bearing capacity of wind turbine blades.

In this report focus is on application of sub-components tests and to present recommendations on how to plan and apply sub-component tests. The work is part of the EUDP¹ supported project “Experimental Blade Research – Phase 2” (EBR2). Specific applications will be presented in following reports in the EBR2 project. More descriptions of the theoretical background and illustrative examples can be found in:

- J.D. Sørensen & H.S. Toft: Modeling of uncertainties for wind turbine blade design. Proc. ICOSSAR2013, New York, 2013. [1]
- J.D. Sørensen & H.S. Toft: Modeling of uncertainties and framework for reliability analysis of wind turbine blades. EBR2 report, 2013. [2]
- Toft, H.S. et al.: Probabilistic methods for wind turbine blades. Report RT2, EERA (European Energy Research Alliance) Wind Energy, Sub-programme on Structural Design & Materials, 2013. [3]

Further, the framework for planning of sub-component tests and assessment of partial safety factors is linked to the on-going revision of the IEC 61400-1 standard, where a new informative annex on ‘Calibration of structural material safety factors and structural design assisted by testing’ is being developed with the theoretical basis described in

- Sørensen, J.D. et al.: Safety Factors – IEC 61400-1 – MT01 - background document. Draft, DTU Wind Energy & Aalborg University, Denmark, 2013.

2 UNCERTAINTY MODELING AND TESTS

A large number of relatively inexpensive tests performed at coupon level can be used to model the statistical characteristics of the basic material properties. Sub-component tests can be used to verify

¹ The Energy Technology Development and Demonstration Programme (EUDP) is administrated by the Danish Energy Agency.

computational model for critical details. The number of tests is typically quite limited. Additionally, down-scaled tests can in some cases be an efficient way to decrease the statistical uncertainty. Finally, one (or very few) full-scale test(s) is performed with a prototype of the blade following the requirements in the IEC 61400-23 [4] standard on full-scale testing.

The purposes of tests are among others to verify computational models and to estimate uncertainties in order to be able to determine characteristic values and in some cases partial safety factors. The parameters subjected to uncertainty are assumed to be modelled by stochastic variables and can in general be divided into the following four groups:

1. **Physical uncertainty** also denoted inherent uncertainty is related to the natural randomness of a quantity (e.g. the material tension and compression strengths) due to variability's in the raw material (e.g. glass) and its manufacturing into a material product (e.g. glass fibres).
2. **Measurement uncertainty** is related to imperfect measurements of e.g. geometrical quantities and applied forces.
3. **Statistical uncertainty** is due to limited sample sizes of observed quantities. Data of observations are in many cases scarce and limited for which reason the parameters of the random variables cannot be determined exactly. If additional observations are provided the statistical uncertainty may be reduced.
4. **Model uncertainty** is the uncertainty related to imperfect knowledge or idealized mathematical models used. Also uncertainty related to the choice of probability distribution types for the stochastic variables contains model uncertainty.

Another 'type' of uncertainty which is not covered by these methods is gross errors or human errors. These types of errors can be defined as deviation of an event or process from acceptable engineering practice and is generally handled by quality control. The effect of the quality control can e.g. be modelled using conditional probabilities or Bayesian statistical methods.

Five groups of tests are considered:

1. **Coupon tests** are experiments with small test specimens from which specific material properties (e.g. strength and stiffness) can be estimated. The tests are typically performed in order to estimate the physical uncertainty.
2. **Numerical simulation tests** are application of more accurate and typically more advanced mathematical models like e.g. finite element analysis. The numerical simulation tests can be used to estimate a part of the model uncertainty when the simulations covers the whole application field. This is done by performing numerical calculations / tests for combinations of material and structural properties over the whole application field and where only a limited part of the combinations are covered by physical tests.
3. **Sub-component tests** are tests with parts of the full structure e.g. a section or detail of the blade. These tests can be used to estimate the model uncertainty relate to the load bearing capacity for a specific component and / or failure mode.
4. **Downscaled tests** are tests performed on a replica of the full structure produced at a smaller scale. In order to estimate the model uncertainty it is necessary to take the scale-effect between the full-scale and the down-scaled structure into account. In many cases the scale effect is difficult to handle and limits the relevance of down-scaled tests.
5. **Full-scale tests** are performed with the full-scale structure from which the model uncertainty can be estimated directly. The full-scale tests are often performed as proof-loading where the test is stopped at the required load which usually is before failure.

It is important to note that in most cases the tests are performed in a laboratory (or laboratory similar conditions) using idealized conditions which only partly are representative for the real conditions. The tests will therefore only be able to describe a part of the uncertainties related to the design.

For all types of tests it is important that a test plan is made in order to specify the objectives and limitations along with documenting the results. According to [5] and [6] the test plan should cover the following:

- Objectives and scope, incl. limitations of tests and (e.g. scale effects).
- Prediction of test results. The expected failure modes and calculation models, together with the corresponding variables should be described.
- Specification of test specimens and sampling: dimensions and tolerances, material and fabrication of prototypes, number of test specimens, constraints and sampling procedure, which is the process of selecting a representative portion of specimens to the tests.
- Loading specifications.
- Testing arrangement.
- Measurements.
- Evaluation and reporting of the tests.

When evaluating test results, the behaviour of test specimens and failure modes should be compared with theoretical predictions (if the objective is to verify a model and estimate the model uncertainty). The evaluation of the test results should be based on statistical methods, with the use of the available statistical information. Generally, the following conditions should be satisfied:

- The statistical data (including prior information) are taken from identified populations which are sufficiently homogeneous and a sufficient number of observations are available.
- The results from an evaluation of a test should be considered valid only for the specifications and load characteristics considered in the tests. If the results are to be extrapolated to cover other design parameters and loading, then additional information from previous tests or from theoretical bases should be used.

3 ESTIMATION OF UNCERTAINTIES

The physical and statistical uncertainty related to a material parameter can be estimated using different approaches and combinations of these e.g. the Maximum-Likelihood method, Bayesian statistics and Bootstrapping, see [1] and [2].

Model uncertainty can be assessed if a mathematical model is introduced to describe / approximate the resistance for a given failure mode. The mathematical model is assumed to be a function of a number of *physical uncertainties* (e.g. strength parameters) modelled by stochastic variables \mathbf{X} with realizations denoted \mathbf{x} . Further, the model is assumed to be a function of a number of regression parameters denoted R_1, \dots, R_m . The regression parameters are determined by statistical methods, and are therefore subject to *statistical uncertainty*. The model is generally not perfect; therefore *model uncertainty* has in general also to be introduced. In [1] and [2] two approaches are described:

- one approach based on the procedure in the EN 1990, [6]
- one approach using a general methodology where classical as well as Bayesian statistics can be applied thereby making it possible to include subjective, prior information

4 APPLICATION FOR SUB-COMPONENT TESTS

Using the uncertainties quantified in section 3 and models for the load bearing capacity assessed by tests, then characteristic values and partial safety factors can be derived. The details are described in [1] and [2].

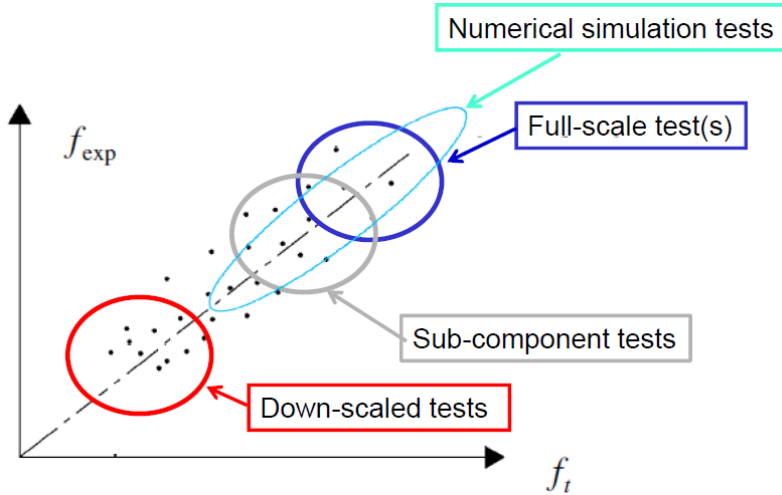


Figure 2. Illustration of tests performed for assessment of model uncertainties. f_t and f_{exp} represent the load bearing capacity obtained by a theoretical / numerical model and by experimental tests, respectively.

Figure 2 illustrates how tests at different scales and type can be pooled together if the conditions mentioned above are fulfilled. This includes among other things that the tests deal with the same failure mode and that scale effects are accounted for. For each test the f_t value corresponds to the predicted load bearing capacity using a general model corresponding to what is expected in the standard. The f_{exp} value then represents the load bearing capacity found by experimental test and in case of numerical simulation tests this corresponds to the predicted load bearing capacity using advanced and more detailed models, than the general model expected to be used according to the standard.

When testing subcomponents it is important to note that these tests should typically be related to only one failure mode, e.g. buckling or bond-line failure. The test setup (boundary conditions, applied loads, ...) should thus be selected such that they represent as well as possible the conditions for the considered failure mode in the full-scale blade.

When performing subcomponent tests the importance of scale effects should be considered carefully, especially if the load bearing capacity depends on the number, location and size of defects. If the load bearing capacity depends on the largest defects and the defects are homogeneously distributed then the full-scale model compared to a subcomponent model has a relatively larger likelihood of having a large defect and therefore a relatively lower load bearing capacity. Further, in some cases subcomponent tests can be applied to formulate / calibrate a computational / analytical model.

The framework and recommendations presented above will be applied in the EBR2 project on sub-component tests related to adhesive joints in the trailing edge in wind turbine blades. Here focus is on the load bearing capacity of the adhesive joints. Sub-component tests have been and are being performed at two levels:

- Level 1 with small test specimens consisting of two laminates glued together and exposed to different load combinations, see [7] for details. The size of the test specimens are 300 x 30 mm with laminate thickness = 8 mm and adhesive thickness = 7 mm. The tests can be used to assess and calibrate a numerical model to estimate the load bearing capacity and to estimate bias and model uncertainty of the numerical model.
- Level 2 where sub-components of blades are exposed to loads corresponding to real loads. The width and length of the sub-components is of the order 1.0 – 1.5 m. Based on the numerical model developed and calibrated on level 1 the load bearing capacity of the sub-components are determined and compared to the results of the tests. Further, coupon tests will be performed to determine material characteristics of the laminates and the adhesive. Based on a number of sub-component tests the bias and model uncertainty of the numerical model is estimated when applied to the sub-sections using the recommended framework described in [1], [2] and [3].

5 ACKNOWLEDGEMENTS

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